Common-Arm Counterpropagating Interferometer for Measurement of Vibration-Induced Noise in Fibers

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***Abstract*—We propose and demonstrate a novel technique to measure the vibration sensitivity of fiber-based optical components. It uses a common-arm counterpropagating frequency-shifted interferometer that reduces the vibration-induced phase noise of the interconnecting fibers feeding the signal to and from the vibrating device under test. The noise introduced by the vibrating fibers can be excessive, and measurements of a given device cannot be made with assurance. The proposed technique improves the vibration-induced phase noise floor by more than 30 dB compared to a conventional frequency-shifted Mach–Zehnder interferometer and allows measurement of low vibration sensitive devices. A phase sensitivity of 1 mrad/g at 192 Terahertz (THz) is achieved with this method. We also present results of vibration sensitivity of an assortment of commonly used fiber-based optical devices.**

***Index Terms*—Interferometry, optical fibers, phase measurement, phase noise, vibration measurement.**

I. Introduction

THERE is a growing need for low phase modulated (PM) noise and low vibration sensitive oscillators for many applications such as radar, navigation, spectroscopy, and timing. In recent years, ultra-low PM noise microwave signals have been generated by dividing optical signals from stabilized lasers. This division from the optical to microwave domain has resulted in extremely low PM noise of -101 dBrad^2/Hz or lower at 1 Hz offset from a 10 Gigahertz (GHz) carrier [1]. Opto-electronic oscillators (OEO) have also been used to generate low noise microwave signals by use of a modulated optical carrier [2]. Presently, the lowest PM noise has been achieved only in quiet, low-vibration laboratory environments. The vibration sensitivity of an OEO is on the order of 10^{-8} to 10^{-10} per g (1 g is the acceleration of gravity near the earth's surface, approximately 9.8 m/s^2), and arises mostly from the length fluctuation of the OEO's long optical fiber that acts as a resonator [3]–[5]. However, there is little information on the vibration sensitivity of fiber-based optical components [6]. The focus of this letter is to study the noise performances of an assortment of such optical components under vibration.

A conventional frequency shifted Mach–Zehnder interferometer (MZI) for measuring vibration sensitivity of fiber-based optical devices is shown in Fig. 1. During the course of setting up a measurement of vibration sensitivity, the interconnecting fibers (F_1 and F_2 in Fig. 1) that deliver the optical signal to and from the device under test (DUT) were so sensitive to vibration that the measurement of a given device could not be made with assurance. Since these delivery fibers cross between the stationary reference frame and the moving frame of the vibration actuator, they undergo not only vibration due to the actuator, but also bending and stretching between the two frames. Mechanical distortion of the core and surrounding cladding causes fluctuations in the phase of the optical signal passing though the fiber [3]. Many fiber-based optical components are connected via integrally included optical fiber 'pigtails' (F_A and F_B in Fig. 1). The sensitivity of these pigtail fibers cannot be ignored and must be viewed as an integral part of the DUT. The effect of these pigtail fibers are not to be confused with, and should be separated from, the delivery fibers that connect the DUT on the vibration actuator to the measurement interferometer. Unfortunately, in many cases the delivery fibers that bridge the stationary and vibratory frames undergo larger phase fluctuations than those experienced by the DUT being evaluated. In this letter, we propose and experimentally demonstrate a novel scheme for reducing the vibration effect on the interconnecting delivery fibers while measuring the vibration sensitivity of an assortment of optical fiber-based components. Sections II and III constitute the technical portion of this letter. Section II describes the setup for reducing the vibration effect on the interconnecting fibers while measuring a component under vibration. Section III discusses measurements results of the optical component's vibration sensitivity.

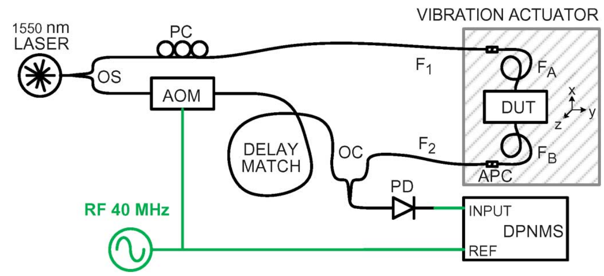

Fig. 1. Block diagram of a conventional frequency-shifted MZI for residual vibration sensitivity measurement of optical devices. PC: Polarization controller. OS: Optical splitter. OC: Optical combiner. AOM: Acousto-optic modulators. PD: Photodetector. APC: Angled physical contact connector. DUT: Device under test. DPNMS: Digital phase noise measurement system. F_1, F_2: Interconnection fibers. F_A, F_B: DUT fiber pigtails. Green lines represent radio frequency signals and black lines represent optical signals. The z-axis is perpendicular to the page.

II. Measurement Methods

In order to measure the vibration sensitivity of a component accurately, it is important to know the noise floor of the measurement system. The initial measurement technique employed to measure the PM noise, and hence the sensitivity of optical components to vibration, is shown in Fig. 1.

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Fig. 1 consists of a frequency-shifted MZI with an erbium-doped fiber laser at 1550 nm as the optical source. A 40 Megahertz (MHz) acousto-optic modulator (AOM) is connected to the reference path of the interferometer, shifting the frequency of the laser by 40 MHz and translating the output of the MZI from baseband to radio frequency for analysis. The DUT, mounted on a vibration platform, is inserted in the nonshifted measurement path of the MZI. The lengths of the two paths are kept almost equal, to minimize differential delay. Finally, the 40 MHz beat at the output of the photo-detector (PD) is amplified and measured on a direct-digital PM noise measurement system. All fibers used in the system are single-mode fiber (SMF-28). Traditionally, vibration sensitivity is given by Γ_y, which is defined as the ratio of fractional frequency fluctuations to acceleration [4]. For devices such as resonators and delay lines, fluctuations in the length (l) or delay (τ) are often normalized as $\delta l/l$ or $\delta\tau/\tau$. The vibration-induced phase fluctuations observed for short fibers are not necessarily proportional to their lengths. Therefore, an alternate vibration-phase sensitivity, Γ_φ, for two-port devices can be defined as

$$\Gamma_\varphi = \sqrt{S_\varphi(f)/S_g(f)} \quad \text{rad/g}, \tag{1}$$

where, $S_\varphi(f)$ is the double-sideband phase noise in rad^2/Hz and $S_g(f)$ is the root mean square (rms) acceleration power spectral density (PSD). Vibrational effects that are distributed with length are best described using Γ_y. Localized or spot effects due to vibration should not be normalized by total length and can be described with Γ_φ. Conversion to the traditional Γ_y can easily be made with use of the carrier frequency.

To determine the noise floor of the conventional MZI measurement system under vibration, the DUT is removed, and fibers F_1 and F_2 are connected and secured to the vibration platform. For this test, a random white vibration profile of $S_g(f) = 1\ \text{mg}^2/\text{Hz}$ is used for $10\ \text{Hz} \leq f \leq 1000\ \text{Hz}$. The vibration phase sensitivity of the conventional MZI is shown by the top green curve in Fig. 2. The noise floor due to the bending and stretching (length fluctuations) of interconnecting fibers was excessive and thus prohibited the measurement of low-vibration sensitive devices. A different approach was therefore necessary that compensated for fibers F_1 and F_2 while retaining sensitivity of the DUT connected between them. A novel technique using a common-arm counterpropagating frequency-shifted Mach–Zehnder interferometer (CACP-MZI) is proposed and shown in Fig. 3. In this new method the conventional MZI is modified with the addition of four circulators. Two of these circulators, A and D, are mounted on the stationary measurement system, and the remaining two circulators, B and C, are mounted on the vibrating platform. The optical signal is split into two paths by use of a 50/50 coupler. The forward measurement signal path, represented by the blue arrows, propagates through the circulators A, B, the DUT, C and, D as shown in Fig. 3. Similarly, the reverse reference path represented by the red arrows is frequency-shifted by the AOM and propagates through circulators D, C, B and A respectively, while bypassing the DUT. The forward and reverse signals combine at the PD, creating a 40 MHz beat signal that is then analyzed. The noise introduced from the

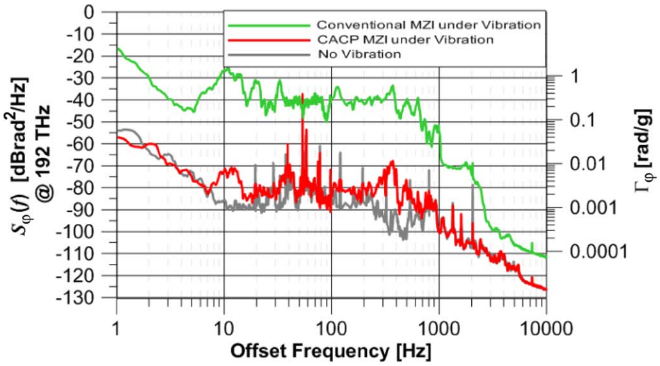

Fig. 2. Vibration sensitivity and residual phase noise floor of the conventional MZI and CACP-MZI under vibration. A random vibration with $S_g(f) = 1\ \text{mg}^2/\text{Hz}$ is used for $10\ \text{Hz} \leq f \leq 1000\ \text{Hz}$. The bottom gray curve shows the noise floor measured under no vibration.

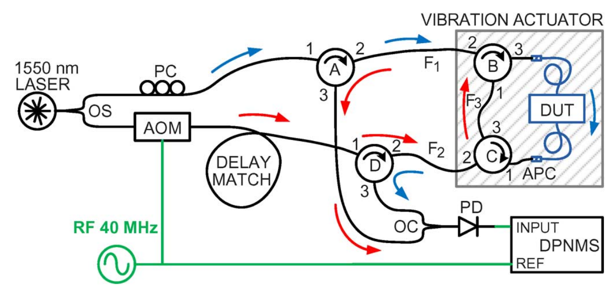

Fig. 3. Common-arm counterpropagating frequency-shifted interferometer for measuring vibration sensitivity of fiber-based optical devices.

flexing interconnecting fibers, F_1 and F_2, is common to both the forward measurement and reverse reference paths and thus is reduced by the MZI, producing a lower noise floor. It should be noted that in CACP-MZI, there is a short uncompensated signal path between ports 2–3 of circulator B, ports 1–2 of circulator C and fiber F_3 that contributes to the noise floor.

The noise floor for CACP-MZI system is measured under the same vibration condition as that of conventional MZI by replacing the DUT with 10 cm of SMF-28 fiber between ports 3 and 1 of circulators B and C. The noise floor for CACP-MZI (shown in red in Fig. 2) is limited primarily by the noise floor under no vibration. An improvement of more than 30 dB over conventional MZI noise floor is observed.

III. Test Results

The optical components considered for vibration sensitivity testing are listed in Table I. The fiber pigtails associated with these components are all 9/125/250 μm SMF-28 fiber. The buffer type and length for each DUT measured are indicated in Table I. For these DUTs, the associated buffer consisted of one of three types, namely, 900 μm tight buffer, 900 μm loose tube, and 3 mm jacketed buffer. In order to understand the sensitivity contribution of the pigtail fibers to the DUT, we first measure Γ_φ of 1 m long optical patch cords of each buffer type. The patch cord is coiled in a 10 cm diameter and is taped on the shaker. For this test, $S_g(f) = 100\ \mu\text{g}^2/\text{Hz}$ from $10\ \text{Hz} \leq f \leq 1000\ \text{Hz}$ is used. For each fiber patch cord, Γ_φ varied depending on the amount of stress induced by the tape securing the fiber coil. Under different mounting conditions, about one to two orders of magnitude variation in Γ_φ is observed for a given fiber. The min–max plots showing

TABLE I
DEVICES CONSIDERED FOR VIBRATION TEST

Device Under Test	Buffer Type	Pigtail Length (m)
Power Splitter	900 um Loose Tube	1
Circulator	900 um Loose Tube	1
Etalon Filter (Finesse ~ 100, BW = 0.9 nm)	900 um Tight Buffer	1
Erbium-doped Fiber Amplifier (Gain = 23 dB, P1dB = 17 dBm)	900 um Tight Buffer	2
80 MHz AOM	3 mm Jacketed	2
Fiber potted in RTV Silicone	250 um Bare Fiber	0.1

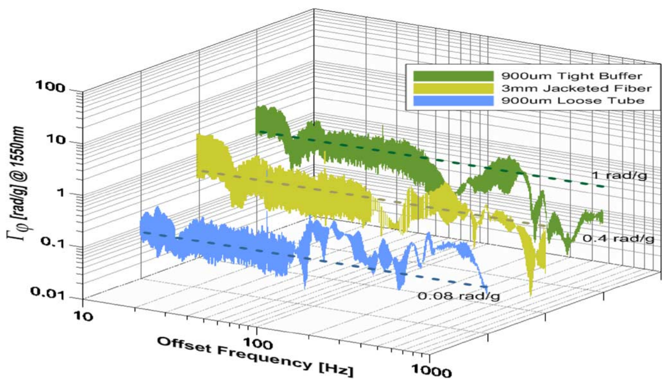

Fig. 4. Min–Max plot showing the variation of the vibration sensitivity of 1-m-long optical patch cords. The response variations above 100 Hz are a combination of resonances from the DUT, its mounting, and the actuator itself.

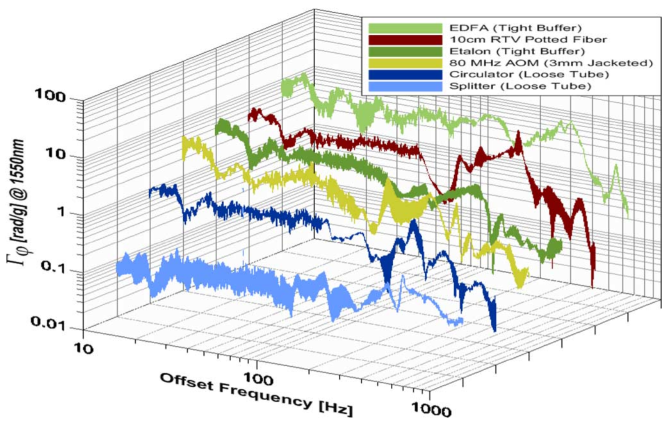

Fig. 5. Min–Max plot of the vibration sensitivity of the various optical components listed in Table I.

this variation of Γ_φ for these three kinds of patch cords are shown in Fig. 4. The result indicates that the loose tube fibers, when constrained with mounting tape, can be less sensitive to vibration than the tight buffered fibers.

Next, the vibration sensitivity of fiber-based optical components are measured under the same vibration conditions, and results are shown in Fig. 5. The vibration is applied only along the z-axis, as shown in Fig. 1. Comparing Fig. 4 and Fig. 5 indicates that the vibration sensitivity of the power splitter, the Etalon filter and the AOM arises mostly from the fiber pigtails, whereas for the circulator and the EDFA, their high sensitivity comes from the device itself, and not from the fiber pigtails. We also tested a 10 cm bare fiber potted in room temperature vulcanized (RTV) silicone. The sensitivity to vibration is found to be nearly two orders of magnitude worse than a nonpotted bare fiber of the same length.

IV. CONCLUSION

We propose and demonstrate a technique to measure the vibration sensitivity of optical fiber-based components. It uses a common-arm counterpropagating MZI, that reduces the vibration-induced PM noise of the interconnecting fibers used in the measurement system. To our knowledge, this is the first implementation of this novel topology. This technique improves the vibration-induced noise floor typically by 30 to 40 dB compared to that of a conventional MZI approach. The proposed system has a sensitivity of nearly 1 mrad/g at 192 THz; therefore, it allows the measurement of low-vibration sensitive optical components. Vibration sensitivity of many optical components is dominated by the sensitivity of the associated fibers pigtails. Constraining the optical fibers to prevent movement is often necessary for repeatability and consistency in fiber-based systems. Stress induced in the fiber due to this constraintment can dramatically increase vibration sensitivity. Different types of buffers used to protect the fiber from other environmental effects can either transmit or isolate the mounting stress to the underlying bare fiber. Loose tube buffering has shown less sensitivity to mounting stress than other buffer types. Careful design of fiber-spool geometry has been used to minimize vibration sensitivity for long lengths of fiber [5]. The sensitivity of the spool has been reduced to levels approaching, or possibly below, the sensitivity due to the interconnecting fibers. If a vibration-insensitive spool of 1 km length were constructed, the connecting 3 mm jacketed fibers ($\Gamma_\varphi = 0.4$ rad/g) would limit the overall fractional vibration sensitivity of the spool to $\Gamma_y = 7\times10^{-11}$/g.

Methods similar to CACP-MZI can also be implemented either with polarization or frequency division multiplexing to combine the reference and measurement path in a common fiber. These common-arm MZI methods may find additional applications when it is critical to separate environmental noise of the delivery fibers from a remote fiber-based sensor.

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